

SOX I: ^{144}Ce - ^{144}Pr Antineutrino Generator (CeANG) Deployment in Borexino

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WINP 2015
February 5, 2015
Brookhaven National Laboratory



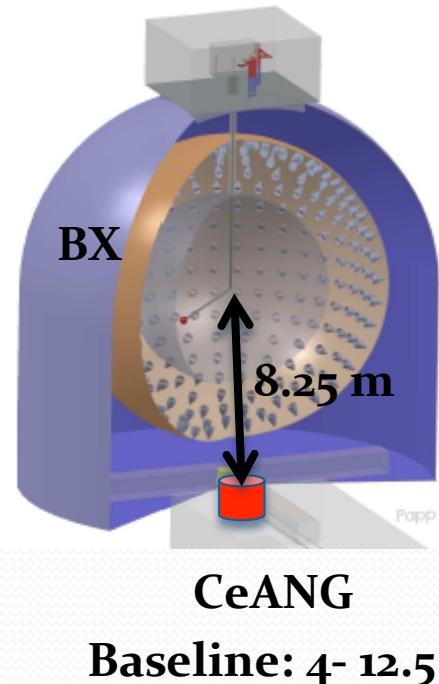
Outline

- Concept of the antineutrino generator experiment for the sterile ν search
- $^{144}\text{Ce}-^{144}\text{Pr}$ antineutrino generator (CeANG)
- CeANG spectrum measurement
- CeANG production
- Backgrounds
- Calorimetric measurement of the CeANG activity
- Shielding, transportation, deployment in Borexino (BX)
- Summary, budget and timeline

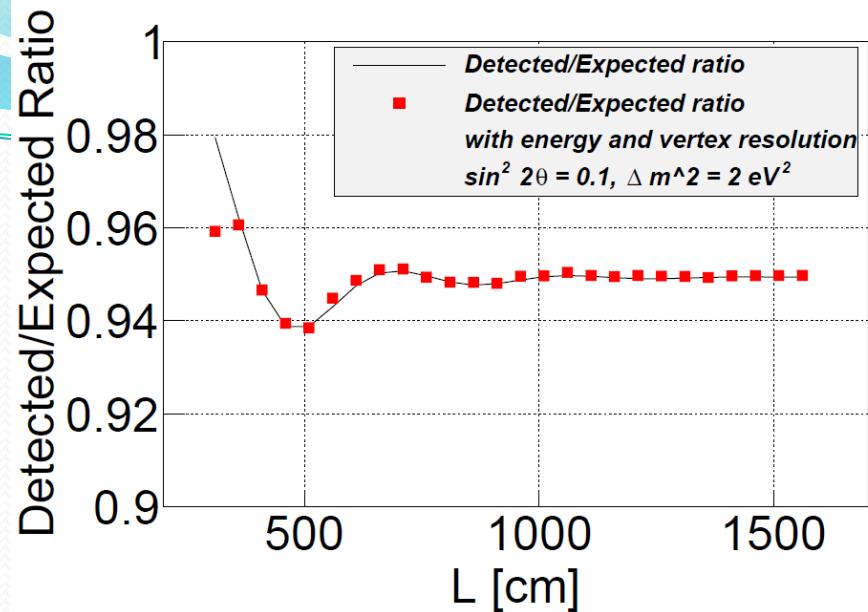
Testing Sterile Neutrino Hypothesis with CeANG

- In case of sterile neutrino
 $\Delta m^2 \sim 1\text{-}2 \text{ eV}^2$,
oscillation distance of interest is of
the order of couple of meters.

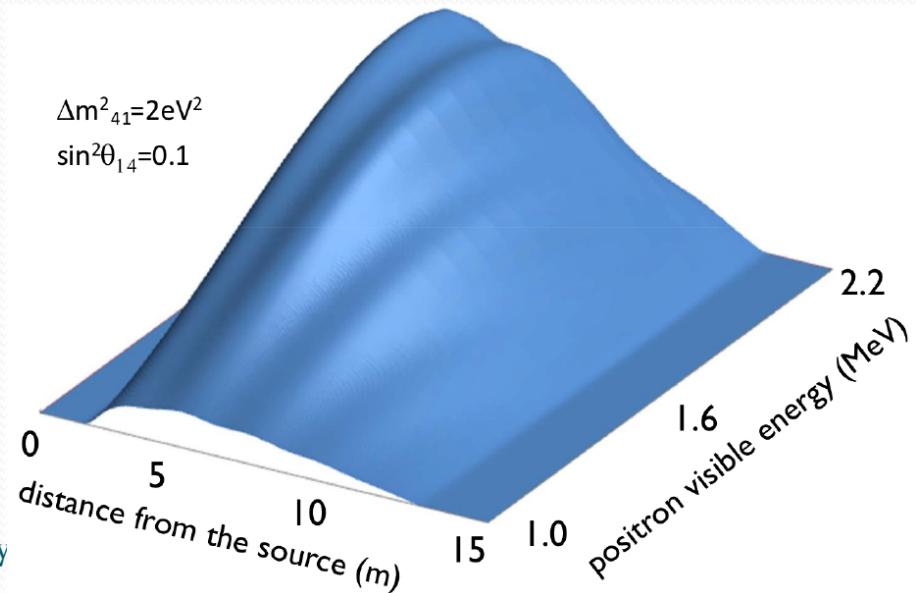
BX ideally suited for such measurement.



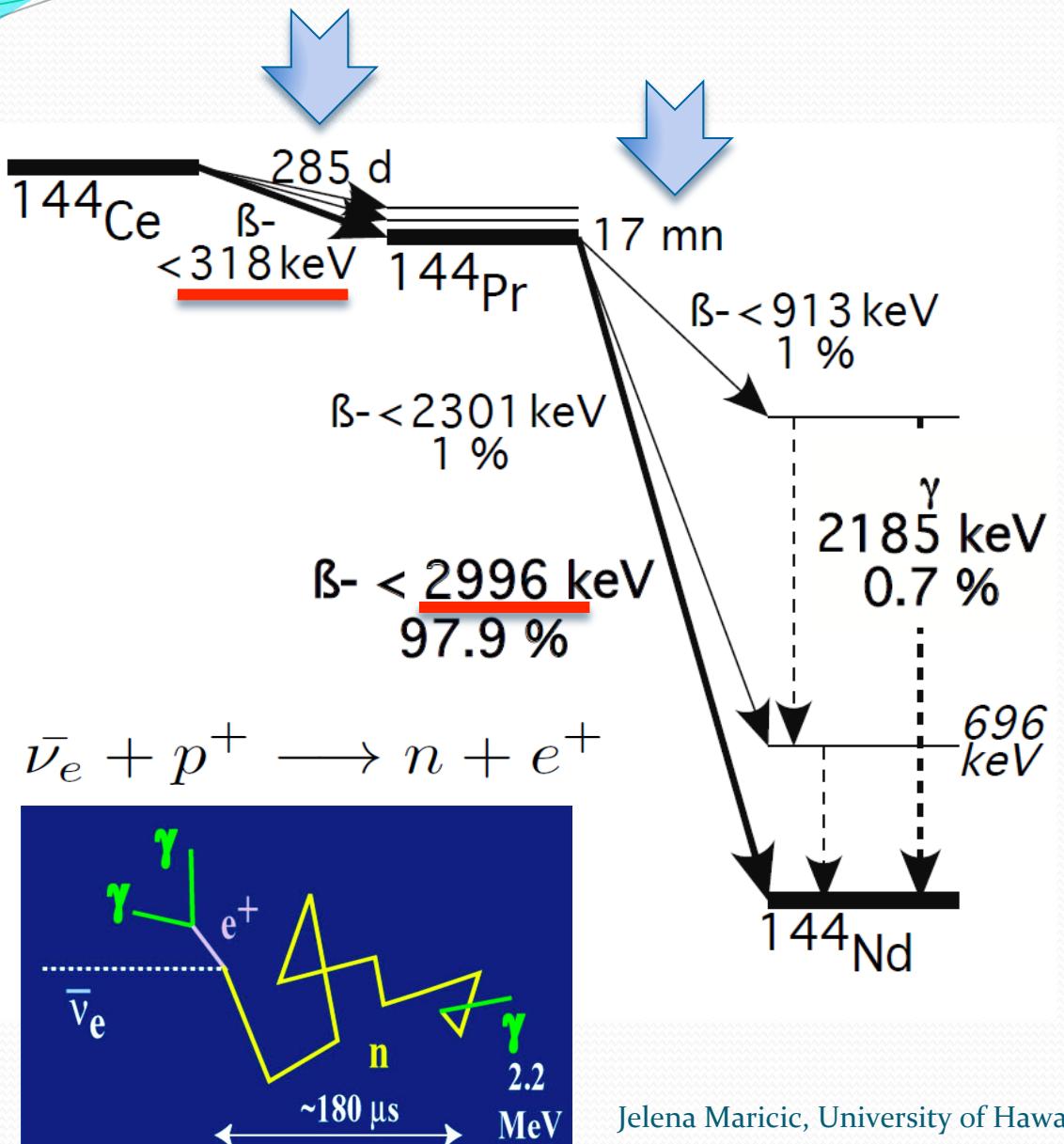
Unique test!
Complementary
to reactor and
accelerator
sterile nu searches.



*Distance dependent shape distortion:
convincing demonstration
of sterile neutrino oscillations.*



$^{144}\text{Ce} - ^{144}\text{Pr}$ Antineutrino Generator

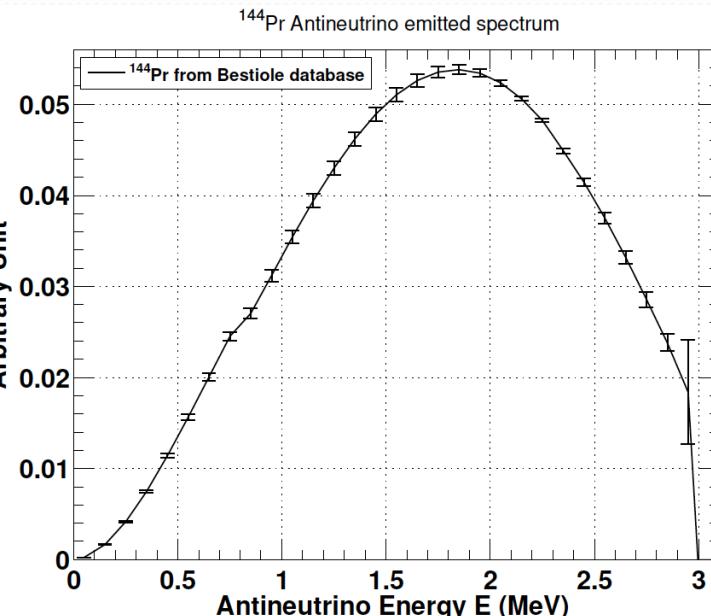
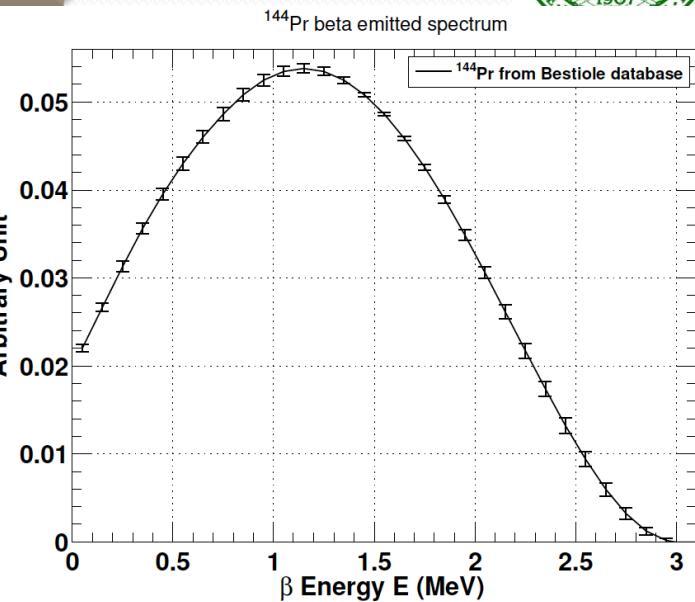
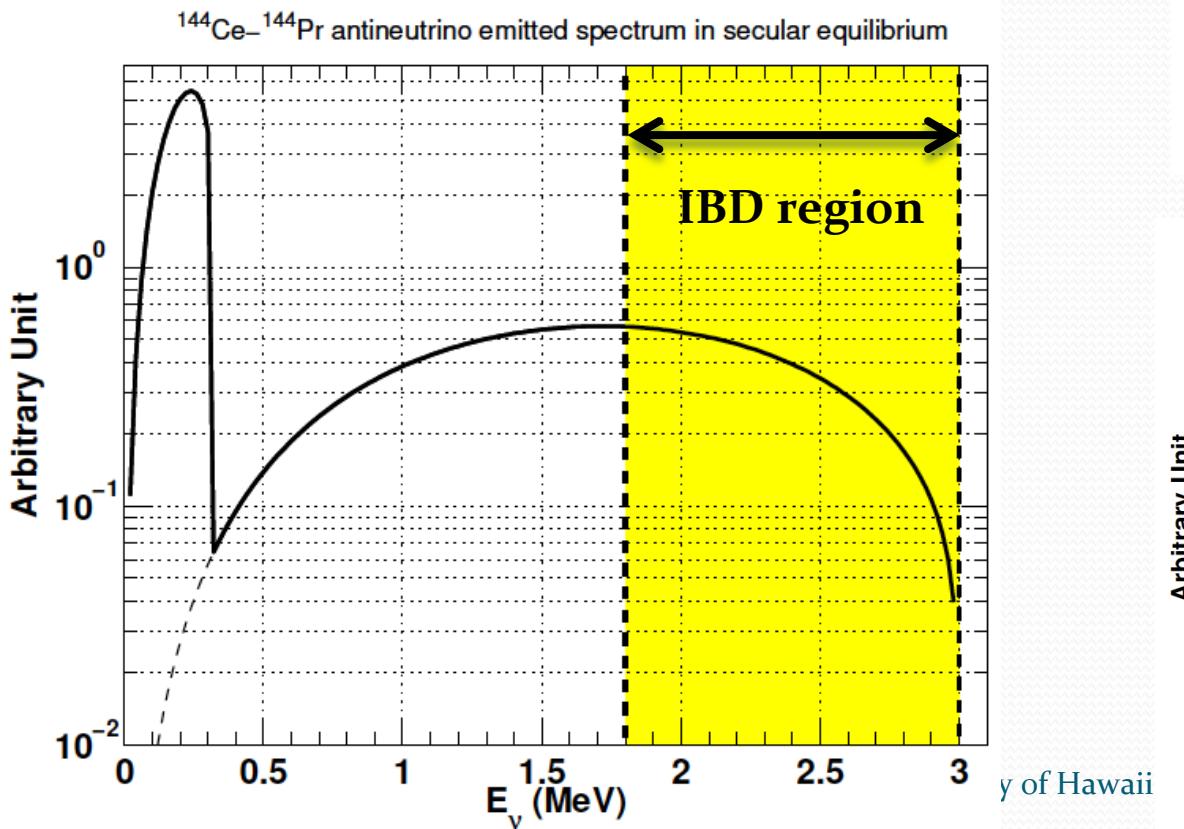


- Nuclei are in equilibrium
- Decay rate completely driven by ^{144}Ce (285 days half-life)
- Antineutrino emitted in ^{144}Ce decay below IBD threshold 1.8 MeV
- Antineutrinos above 1.8 MeV emitted in ^{144}Pr undergo IBD
- 3.7-5.5 PBq source is planned
Expect > 10,000 (possible 30,000!)
- Main intrinsic background comes from 2.185 MeV gamma with 0.7% branching ratio → similar energy as 2.2 MeV de-excitation gamma from neutron capture on hydrogen

$^{144}\text{Ce} - ^{144}\text{Pr}$ Spectrum



- Antineutrino spectrum derived from measurement of ^{144}Pr beta spectrum.
- Precise measurement of the ^{144}Pr spectra necessary to take full advantage of rate/shape analysis → how well do we know it?



Status of the ^{144}Pr β Spectrum Measurements



Author(s)	Instrument	Shape factor $C(W)$	E_0 [keV]	Change in shape factor
Laubitz (1956) [Lau56]	Lens spectr. 6% resol.	$1 - 0.058W - 0.389/W$	2990 ± 10	Decreases by 21% in (640 – 2700) keV
Graham et al. (1958) [GGE58]	Double lens spectr.	$1 + 0.0146W + 0.0283/W$	2984	Increases by 3% in (500 – 2500) keV
Porter and Day (1959) [PD59]	Argon double lens	$1 + 0.028W + 0.091/W - 0.0041W^2$	2992	Decreases by 5% in (500 – 2700) keV
Daniel and Kaschl (1966) [DK66]	Heidelberg double lens	$1 + 0.03W - 0.118/W - 0.008W^2$	2996 ± 3	Decreases by 7% in (1200 – 3000) keV
Nagarajan et al. (1971) [NRVR71]	Intermed. image spec- trometer	$1 - (0.0975 \pm 0.013)/W$	3000 ± 4	Increases by 2% in (1200 – 3000) keV
Bosch et al. (1973) [BBC ⁺ 73]	Scintillating Crystal	$1 + 0.33/W$	3002 ± 5	Decreases by 20% in

Shape of energy spectra:

$$N(W) \propto \underbrace{W \cdot p \cdot (W - W_0)^2}_{\text{statistical shape}} \cdot \underbrace{F(W, Z)}_{\text{Fermi func}} \cdot \underbrace{C(W)}_{\text{shape factor}}$$

W : total energy of electron

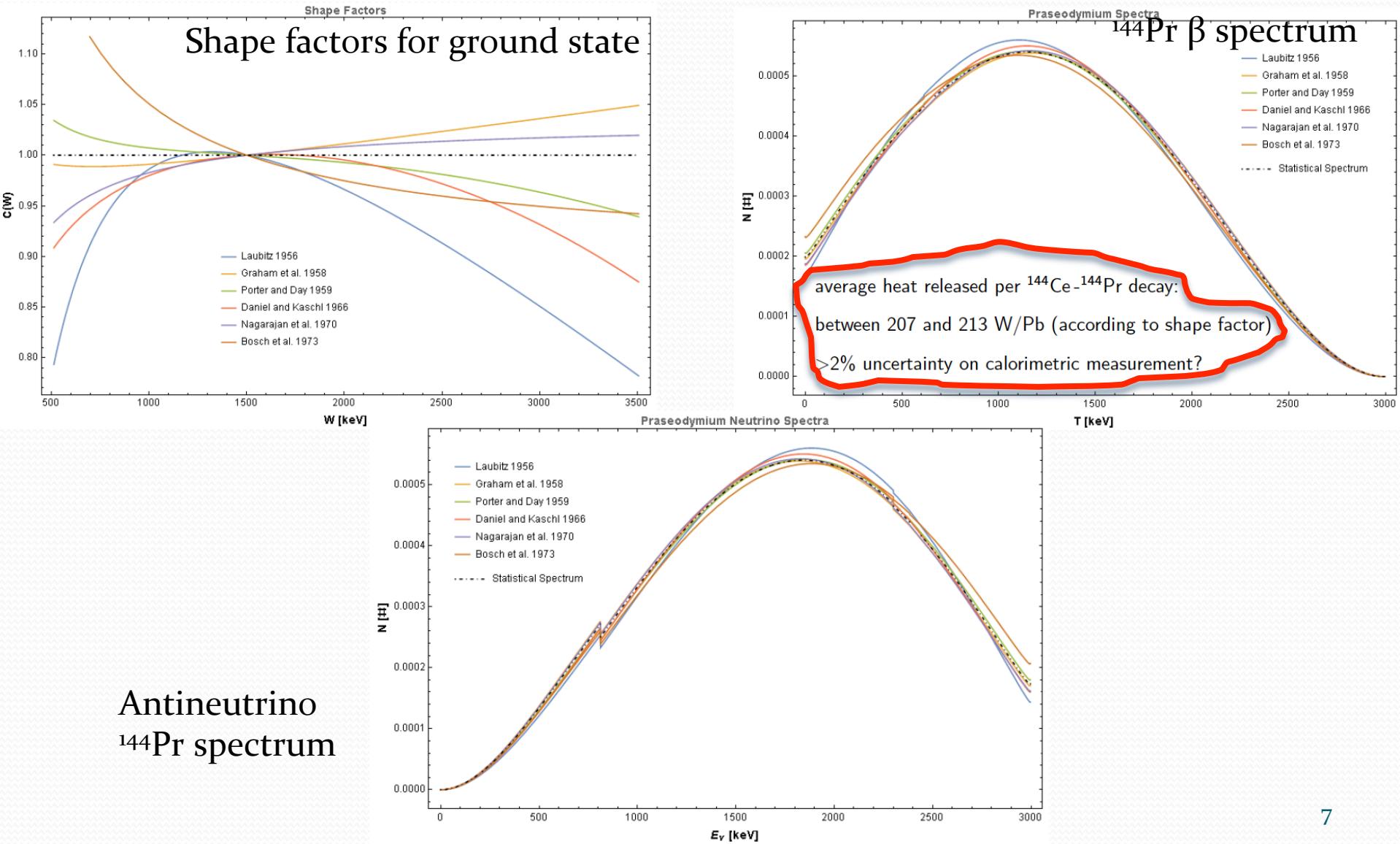
W_0 : end point

p : electron momentum

$C(W) = \text{const} + a \cdot W + b/W + c \cdot W^2$
(parametrization for $^{144}\text{Ce} - ^{144}\text{Pr}$)

Shape Variation from Different Measurements

Main ^{144}Pr branch (97.9%): ground state $\text{o}^- \rightarrow \text{o}^+$ first non-unique forbidden transition

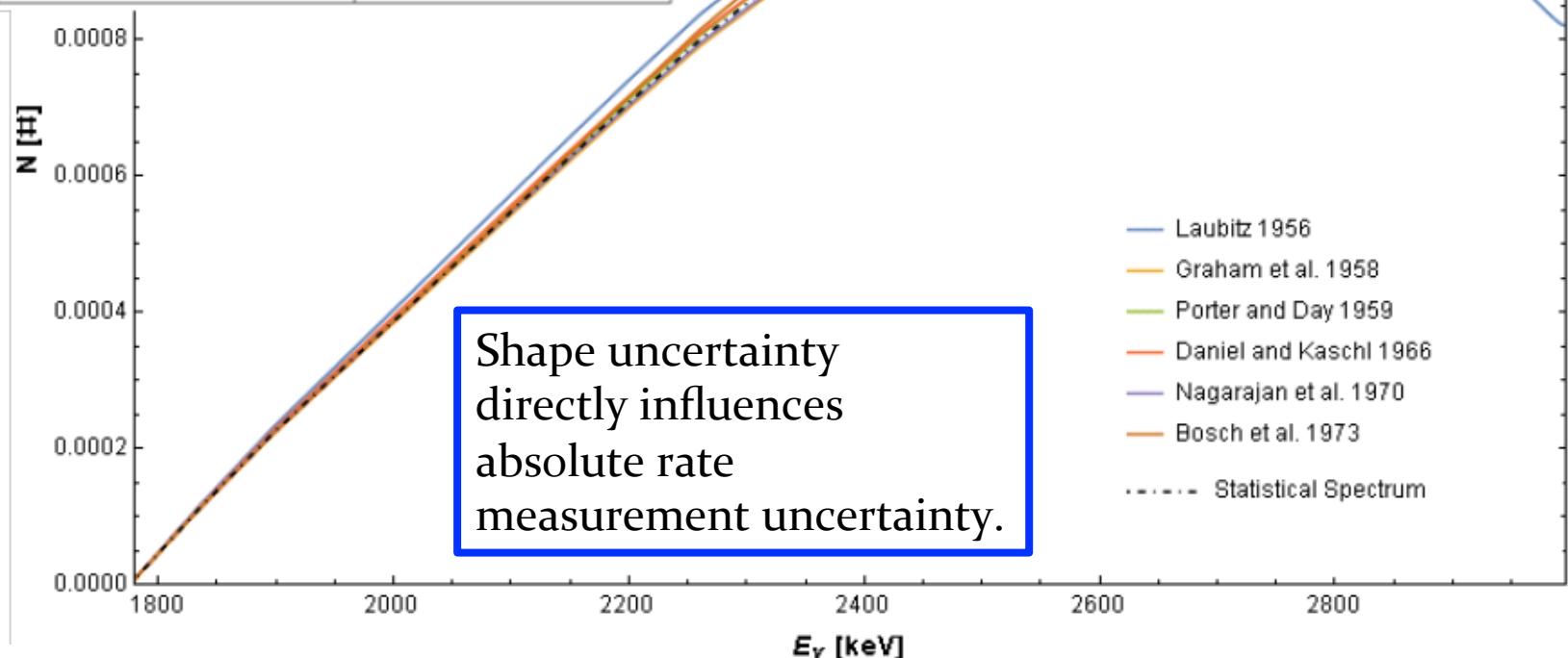


Antineutrino
 ^{144}Pr spectrum

Antineutrino Interaction Rate



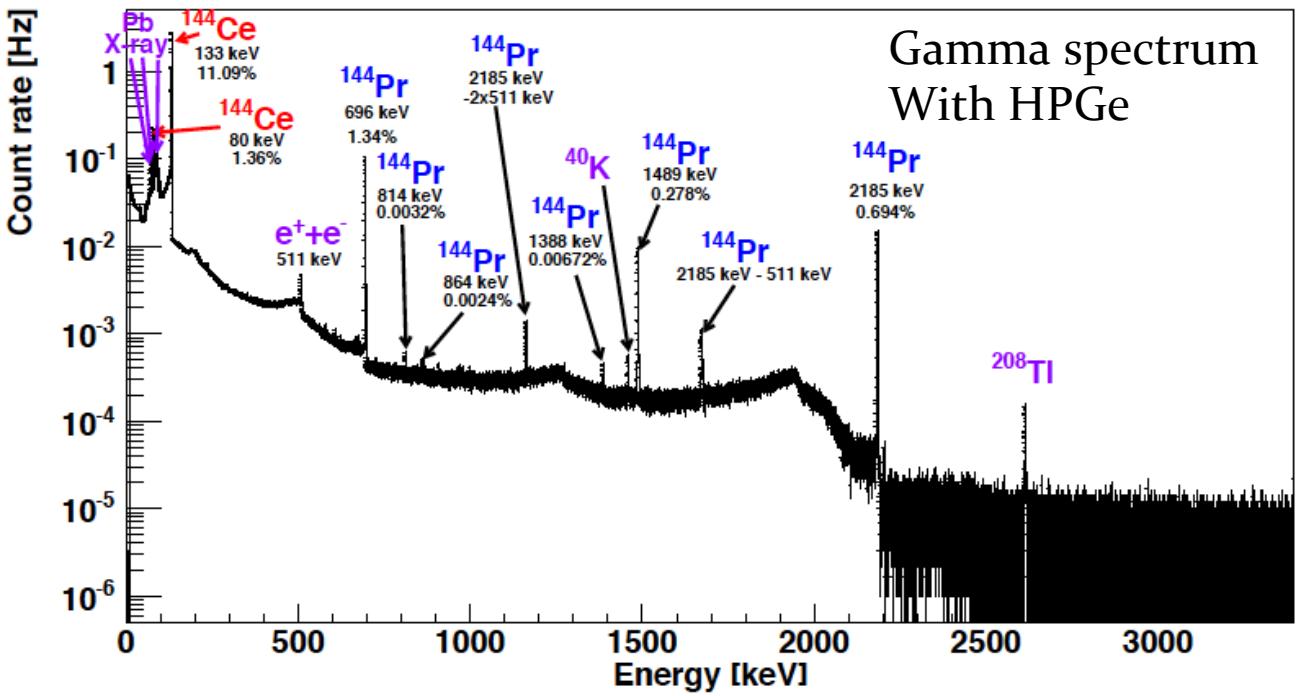
Shape Factor	$\int N_\nu(T_\nu) \cdot \sigma(\bar{\nu}_e p) dT_\nu$
$C(W) = 1$	100%
Laubitz 1956	99.8%
Graham 1958	98.6%
Porter and Day 1959	101.5 %
Daniel and Kaschl 1966	98.8 %
Nagarajan et al. 1971	97.7 %
Bosch et al. 1973	106.7 %



Measurement of the ^{144}Pr Spectrum using ^{144}Ce Samples



- 3 samples of 10 cm³ Ce(NO₃)₃ - 59 kBq ^{144}Ce each
- Goal I: Characterization of β/γ impurity content
- Goal II: Measure ^{144}Ce & ^{144}Pr β -spectra. Predict ^{144}Pr ν -spectrum with β -spectrometers
- Goal III: optimization of the process, neutron impurity content



CeANG Production



- Natural cerium is mostly ^{140}Ce (88.45%) in the form of CeO_2 (in oxygen reach environment)
- ^{144}Ce is a fission product, with 5.2% fission yield from ^{235}U : half-life 285 days → much longer than any other Ce isotope
- Long half-life allows time for production from irradiated fuel, transport to reprocessing facility and year and a half long deployment in the LS detector
- *Fresher irradiated fuel has a higher ^{144}Ce fraction leading to higher source activity, important for the oscillation measurement*



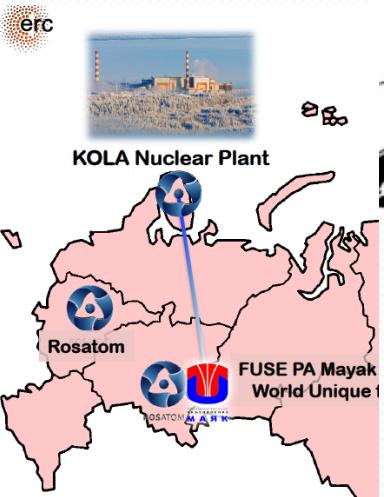
CeANG Specification

- Produced by Mayak reprocessing plant in Russia.
- Activity 3.7-5.5 PBq (in the form of CeO_2)
- 5.5 PBq $\rightarrow P = 1200 \text{ W}$
- **Source extraction from less than 2 years old SNF**
- **SNF hand picked to maximize ^{144}Ce content**
- Density 4-6 g/cm³
- Must fit inside 15 cm high and 15 cm diameter cylindrical double capsule for SFRM (IAEA regulated)
- Purity data from ^{147}Pm production line
 - Content of any other γ -emitters in Ce $\leq 10^{-3} \text{ Bq/Bq}$
 - Content of Pu and n emitters in Ce $\leq 10^{-5} \text{ Bq/Bq}$

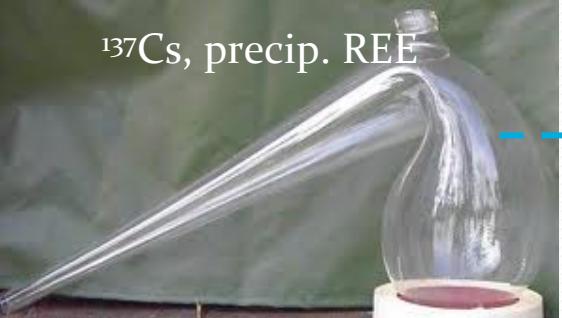


CeANG Production at PA Mayak

Production time - 9 months



PUREX – Plutonium
Uranium Extraction



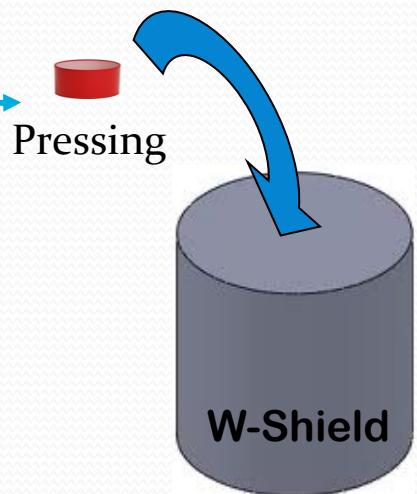
Rare earth elements
precipitation



CeO₂ calcination



Displacement
Chromatography:
Liquid Cerium
solution



Pressing

W-Shield

CeANG Production Concerns

- 1) Production needs to eliminate impurities.
Traces of actinides such as Am, Cm, Bk, Cf can undergo SF or (α, n) reaction that happens in 1% of SF
- 2) The highest risk from ^{244}Cm as it has half-life 18.1 years, isotopic fraction of 1.4×10^{-4} and produces $\sim 2.7 \text{ n/SF}$

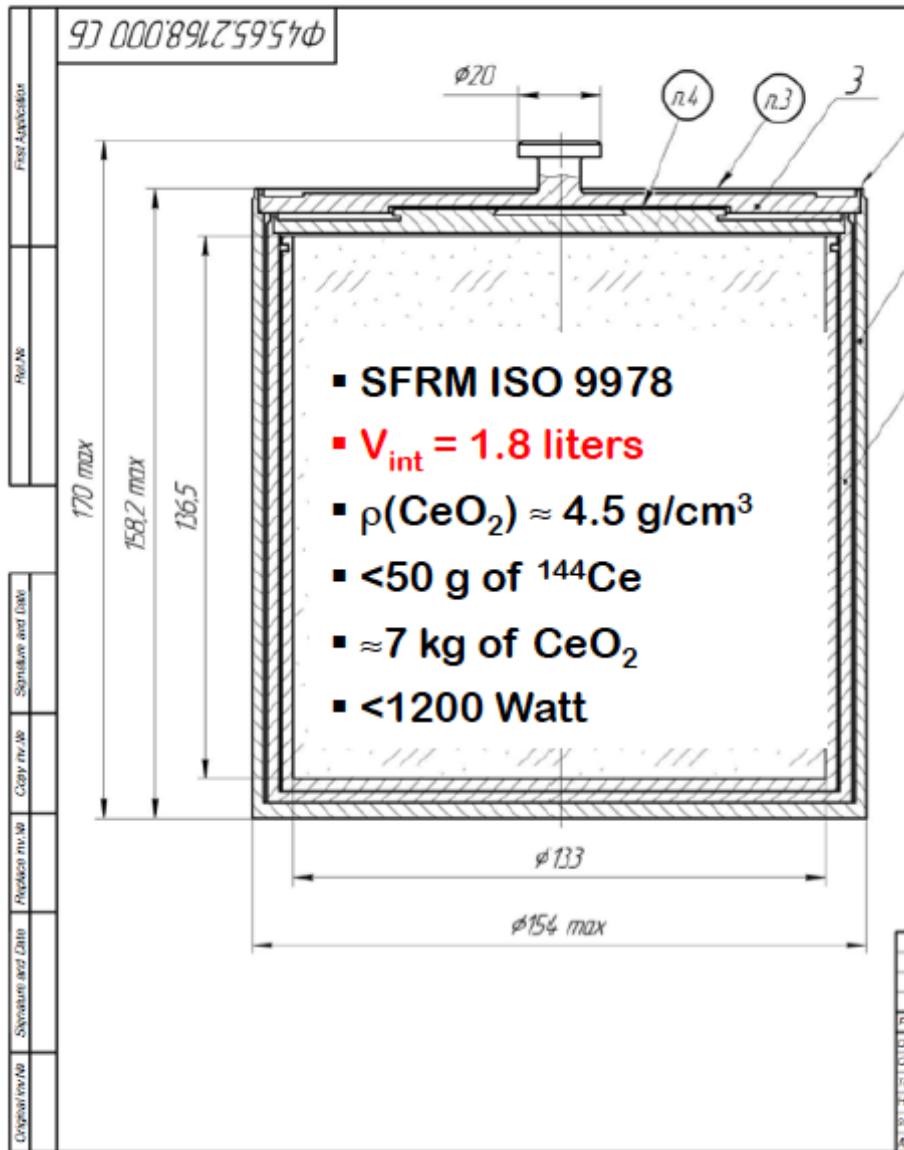
→ Specification $^{244}\text{Cm}/^{144}\text{Ce} < 10^{-5} \text{ Bq/Bq}$ (even 10^{-4} OK for physics)

CeANG sample testing exhibits satisfactory level!

→ $^{244}\text{Cm}/^{144}\text{Ce} = 8(3) \times 10^{-6} \text{ Bq/Bq}$

→ $^{241}\text{Am}/^{144}\text{Ce} = 2(2) \times 10^{-6} \text{ Bq/Bq}$

CeANG Capsule



CeANG is classified as
Special Form of
Radioactive Material (SFRM)

Mayak takes care of SFRM certificate (compliant with IAEA)

- Notes:**
- Assembled and welded using manufacturer's technological process; penetration depth not less than 0.6 mm.
 - Dimensions without tolerances are given for reference only.
 - Marking.**
Marking content:
a) Serial Number;
b) chemical symbol of the element – Ce-144;
c) basic trefoil symbol;
d) year of manufacture
 - Marking.**
Marking content: Serial Number

Rev	Sheet	Document Nr	Signature	Date	Lit	Weight	Scale
Prepared							
Checked							
Technichecked							
Head of DR							
Prints verified							
Approved							

$\phi 45.65.2168.000 CB$

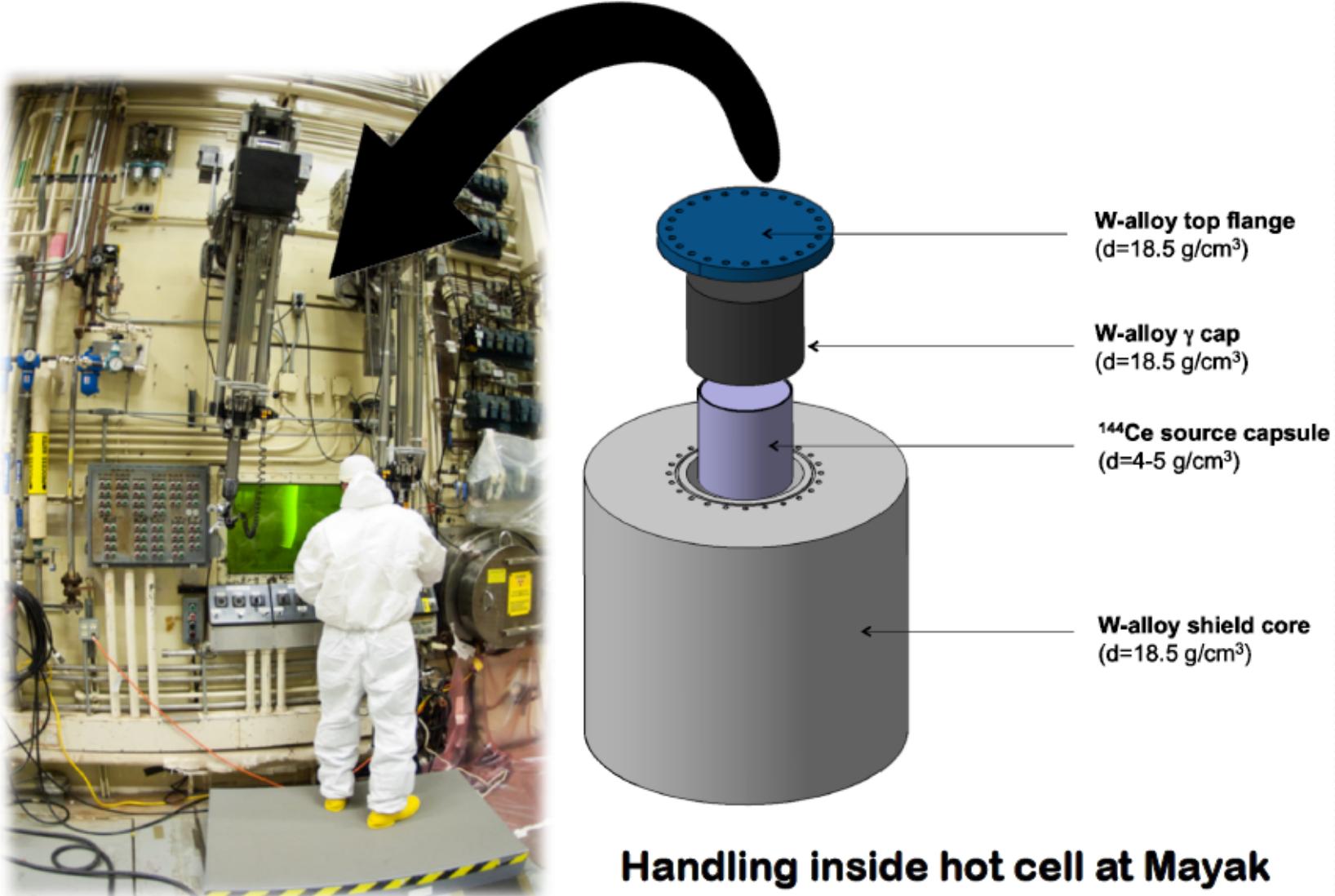
Ce-144 Assembly Drawing

Sheet 1 of Sheets 1

Steel 12X18H10T-ИД** to
State Standard ГОСТ 5632-72

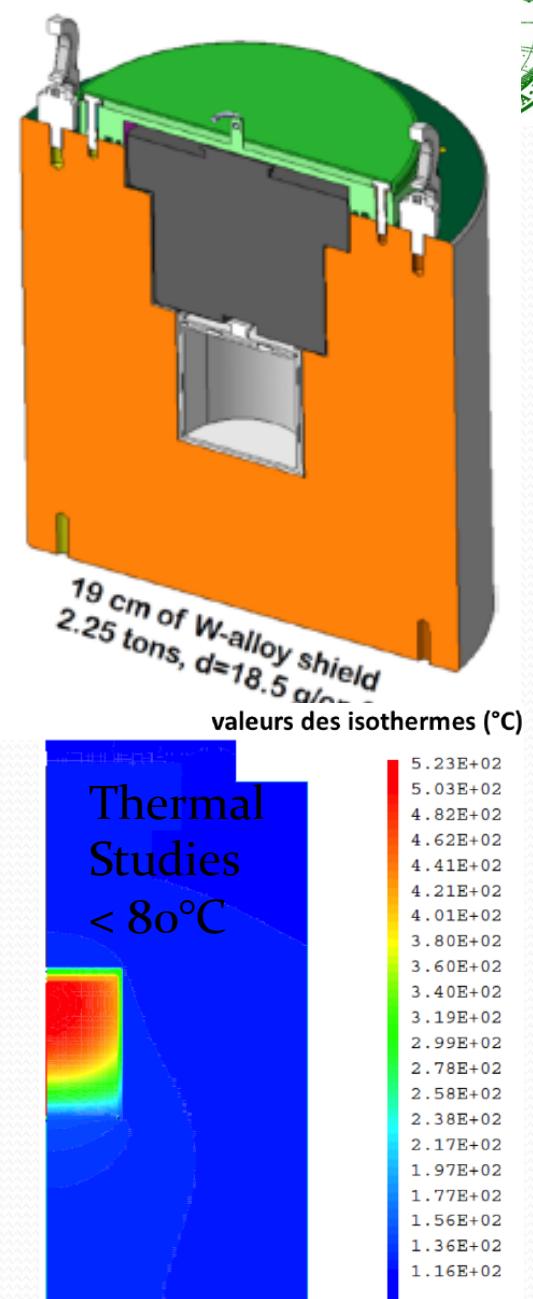
FSUE "Mayak" PA

Insertion of CeANG Capsule in the Tungsten shield at Mayak

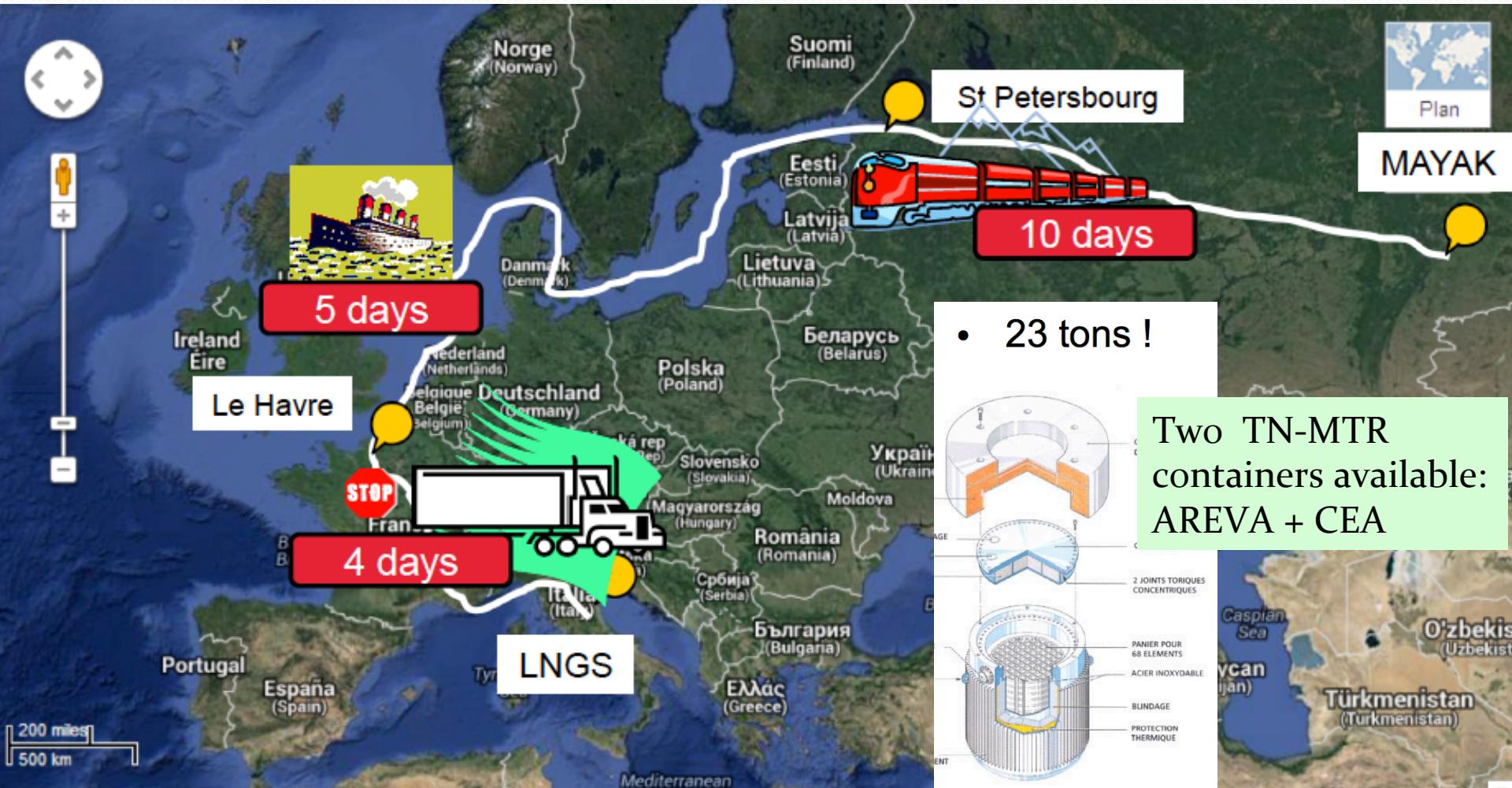


High Z-shielding

- Tungsten shielding that is 95% tungsten and $\rho = 18.0 \text{ g/cm}^3$ will be used (97% tungsten lacks mechanical strength throughout)
- Shielding has two-fold purpose:
 - Biological protection during transportation and handling
 - Suppression of the 2.186 MeV gamma during deployment (0.7% branching ratio)
- 19 cm thick tungsten shield around 5.5 PBq source is sufficient for biological and deployment protection → 2.2 ton weight
- Tender issued; contacted a few companies: Plansee, Xiamen...
- US DOE currently funds 50% of the tungsten shield (\$200k)



Transportation Plan



Licensing and Transportation Status



- Transport feasibility study → done
- TN-MTR licensing for SFRM in France expected by March 2015
- TN-MTR validation in Italy + 5 months
- Transport notice of competitive tender answered by AREVA (500 k€), but other 2 companies interested as well
- *Source production, transportation and licensing covered by INFN/CEA*

CeANG in BX for RAA

Borexino detector

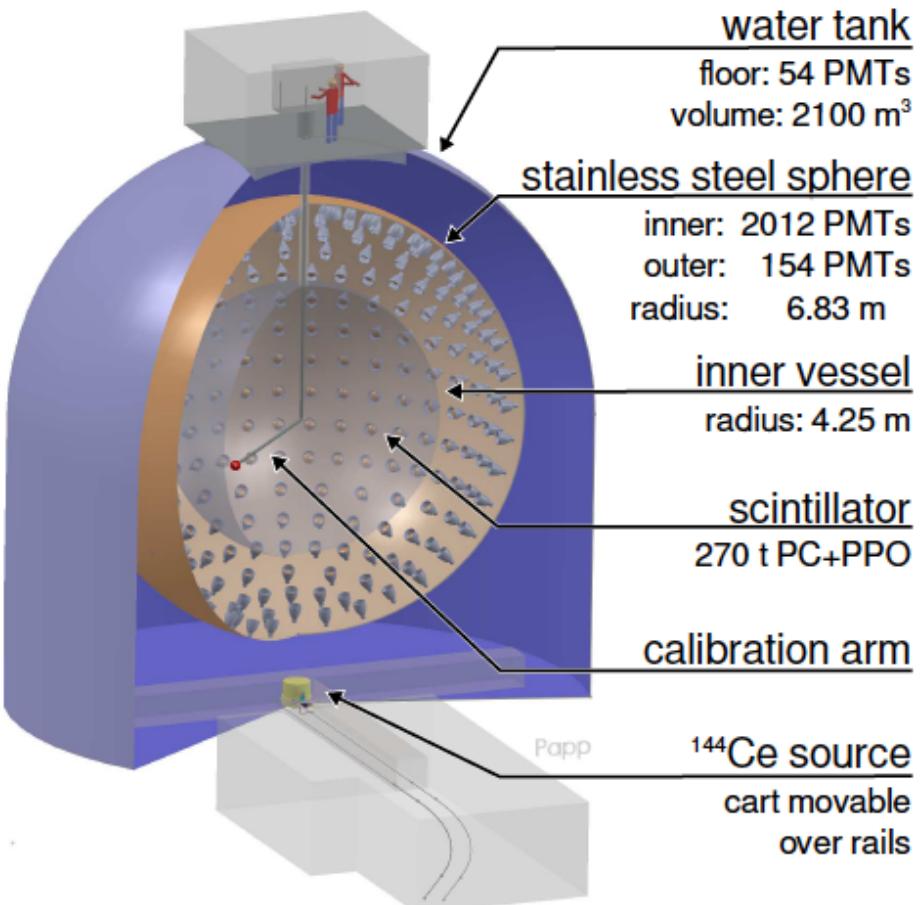
- 270 t of LS
- 2200 PMTs
- Located at LNGS

Sources

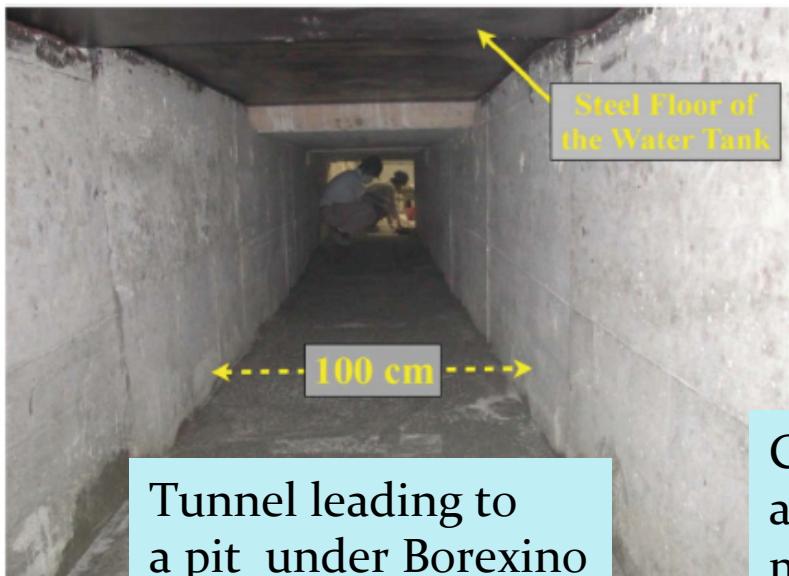
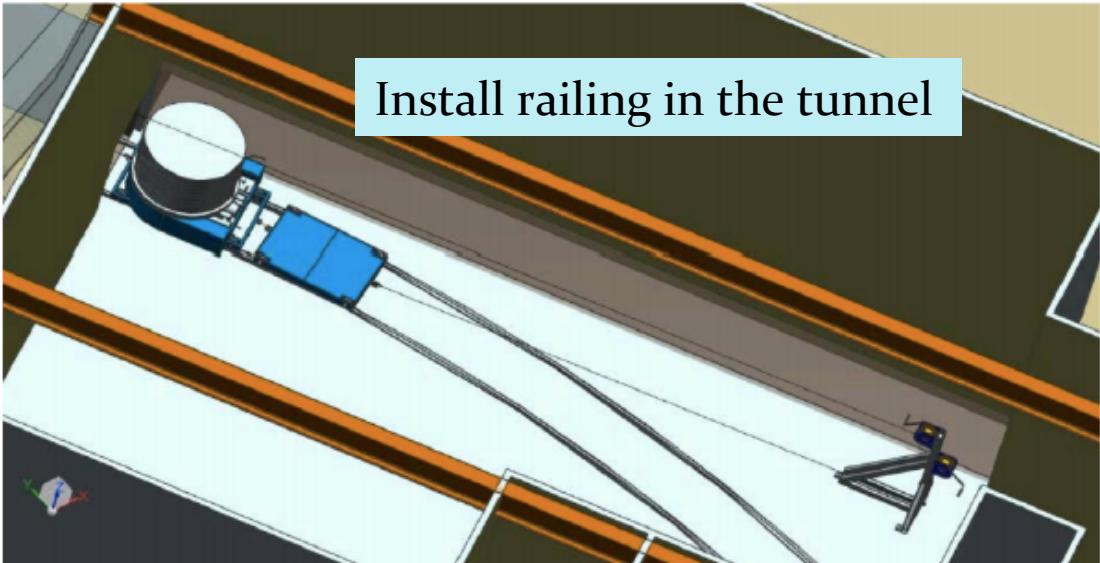
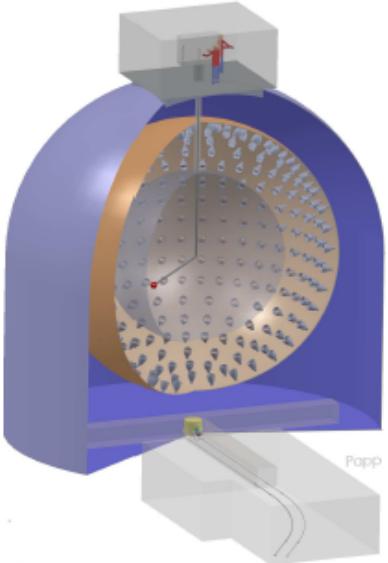
--3.7-5.5 PBq ^{144}Ce - ^{144}Pr ($T_{1/2} = 285$ days)
 10^4 events (x3 possible)

Experiment time-scale:

- June 2016: ^{144}Ce source deployed
- End of 2016: first results
- 2017: ^{51}Cr deployed

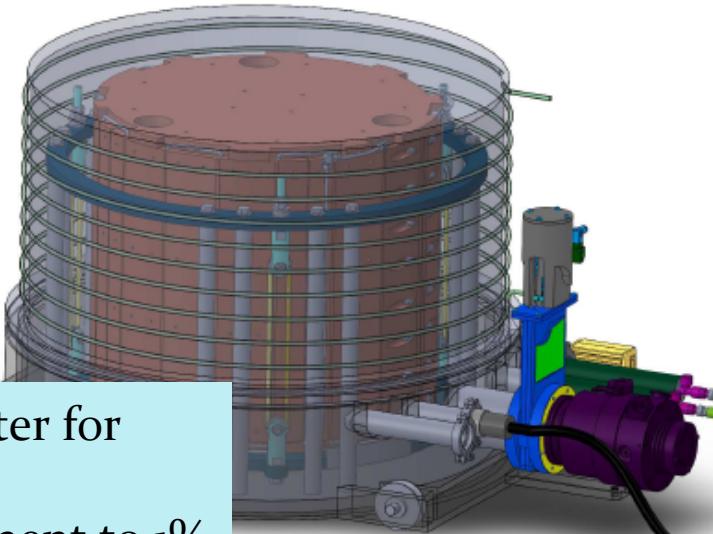


SOX deployment plan and source activity measurement



Tunnel leading to
a pit under Borexino

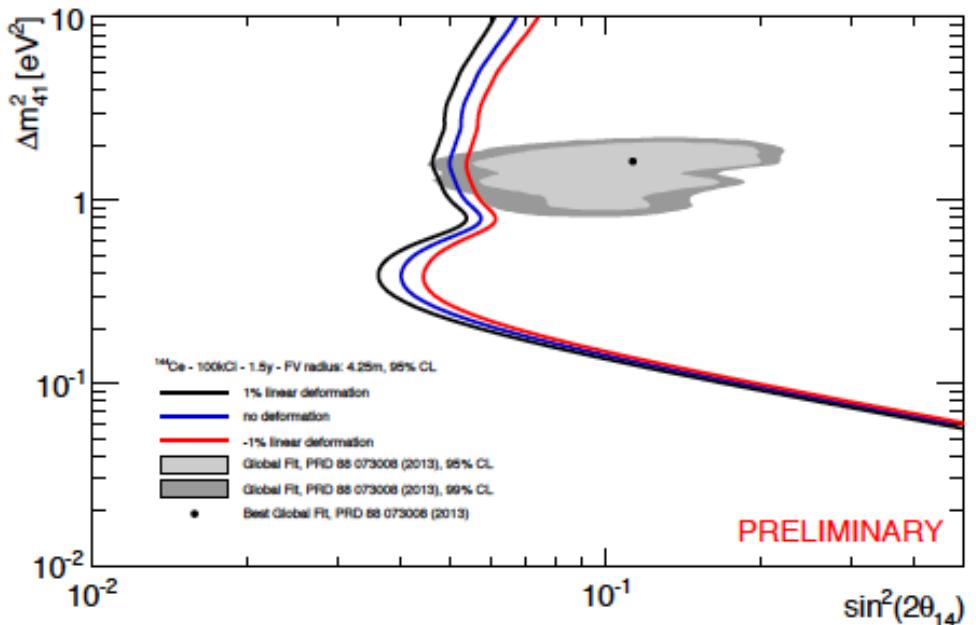
Calorimeter for
activity
measurement to 1%



Sensitivity study

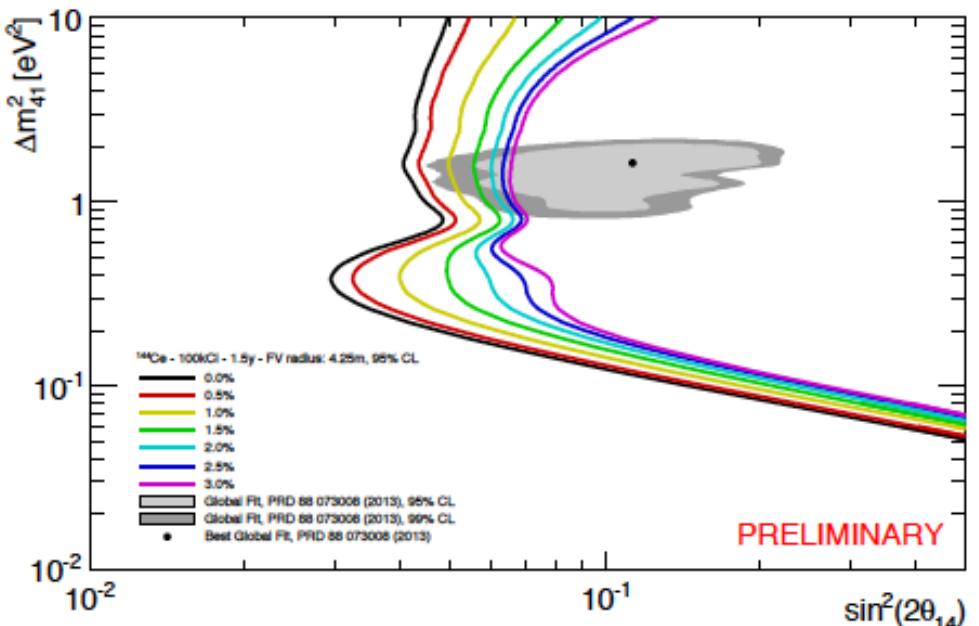
- Systematic uncertainties dominated by anti- ν flux
 - Source activity
 - Neutrino energy spectrum

Energy distribution uncertainties:



PRELIMINARY

Source activity uncertainties:



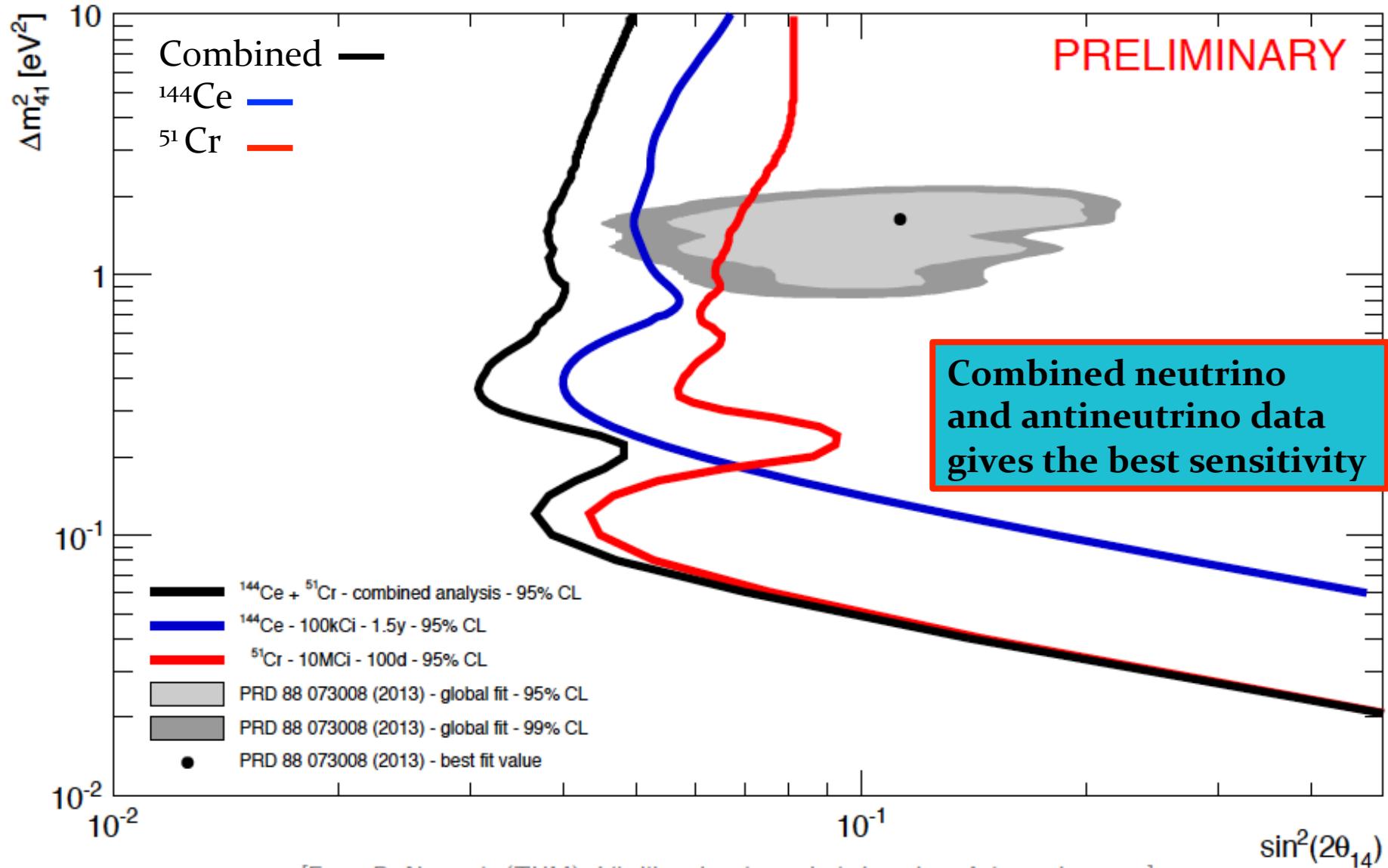
PRELIMINARY

- Borexino has excellent energy resolution
- Source activity uncertainty 1% (calorimeter design + ^{144}Pr beta spectrum measurement)

[From B. Neumair (TUM)].



SOX physics reach





Summary and Timeline

- Unique test (in the entire world) of the 1-10 m neutrino baseline
- Direct and very simple approach for detecting sterile neutrinos in RAA parameter space:
 - well understood, state-of-the-art Borexino detector
 - simple interaction signature
 - extremely low risk from unexpected backgrounds
- Budget: Current direct US participation: 50% tungsten shield (DOE).
Proposed expansions:
 - Full tungsten shield for CeANG (+\$200k)
 - Beta and gamma spectrometer for analyzing $\text{Ce}(\text{NO}_3)_3$ – with ^{144}Ce (\$80k)
- Data taking with ^{144}Ce - ^{144}Pr in summer 2016 and first results in (6 months) → by the end of 2016.
- ^{51}Cr in 2017 – especially exciting in case of positive signal from ^{144}Ce - ^{144}Pr ; great opportunity to study NSI otherwise!



Thank you